OPTIMIZATION MODELING OF THE MISSISSIPPI RIVER VALLEY ALLUVIAL AQUIFER IN ARKANSAS

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ABSTRACT: Conjunctive-use optimization modeling was done to assist water managers and planners by estimating the maximum amount of ground water that hypothetically could be withdrawn from wells within the Mississippi River Valley alluvial aquifer without violating hydraulic-head or stream-discharge constraints. In 1997, nearly 6 million acre-feet of water were pumped from the aquifer by more than 45,000 wells, primarily for irrigation and for fish farming. Several large cones of depression over 100 feet deep have formed in the potentiometric surface, resulting in lower well yields and degraded water quality in some areas. MODFLOW-based ground-water flow models were developed for the north and south portions of the aquifer, primarily in eastern Arkansas. MODMAN optimization models based on these flow models showed that continued pumping at 1997 rates are unsustainable without violating head constraints imposed as a part of Arkansas' Critical Ground-Water Area criteria. One of these criterion states that if ground-water levels drop below half the original saturated thickness of the formation, then a "critical ground-water area" may be designated. In addition, streamflow constraints were established based on minimum flow requirements for maintaining water quality and fish habitat. Preliminary results show that continuous pumping at 1997 rates indefinitely resulted in water levels dropping below the half-thickness constraint, making these rates unsustainable. Optimized sustainable pumping was obtained such that water levels were maintained at or above the half-thickness constraint or a total saturated thickness of 30 feet, and streamflow was maintained at or above minimum levels. Optimized sustainable yields from streams were nearly 2 orders of magnitude greater than for ground water.
KEY TERMS: Ground water; surface water; sustainable yield; optimization modeling; conjunctive-use modeling

INTRODUCTION

The Mississippi River Valley alluvial aquifer, often termed the "alluvial aquifer", is a water-bearing assemblage of gravels and sands that underlies about 32,000 square miles of Missouri, Kentucky, Tennessee, Mississippi, Louisiana, and Arkansas. In Arkansas, the alluvial aquifer occurs in an area generally 50 to 125 miles wide and about 250 miles long. The alluvial aquifer is the uppermost aquifer in this area, and generally ranges in thickness between 50 and 150 ft . Agricultural withdrawals from the aquifer started in the early 1900's for irrigation of rice, and to a lesser extent, soybeans. Water use from the alluvial aquifer in eastern Arkansas increased from 1.18 million acre-feet/year in 1965 to 7.52 million acre-feet/year in 2000—an increase of 537 percent (Holland, 1995). By 1997, nearly 6 million acre-feet of water were pumped from the aquifer each year by more than 45,000 wells, primarily for irrigation and for fish farming. In 2000, 97 percent of the ground water obtained in eastern Arkansas came from wells completed in the alluvial aquifer (T. W. Holland, U.S. Geological Survey, written commun., 2003). .

Water-level declines in the alluvial aquifer were first documented in 1927 (Engler and others, 1945); over time, several large cones of depression over 100 feet deep have formed in the potentiometric surface, resulting in lower well yields and degraded water quality in some areas (Schrader, 2001). Substantial water-level declines in the alluvial aquifer prompted the need to better understand the flow system in the alluvial aquifer, which, in turn, led to the development of digital ground-water flow models of the alluvial aquifer. To address this need, the U.S. Geological Survey in cooperation with the Arkansas Soil and Water Conservation Commission and the U.S. Army Corps of Engineers, began a study of optimization modeling of the alluvial aquifer in Arkansas. The purpose of this paper is to describe preliminary results and to show how these models were used to estimate optimal sustainable yields of ground water and surface water without compromising water levels or stream flow.

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GROUND-WATER FLOW MODELS

Although ground-water flow models had been developed previously for the area, these were either at a scale that was too large to analyze the effects of projected ground-water withdrawals or models were limited in their areal extent. The models discussed here are based on the models of the alluvial aquifer documented by Mahon and Poynter (1993). The alluvial aquifer flow system was modeled as two separate geographic areas--a “north” model area and a “south” model area, each with a common border along the Arkansas River (fig. 1). Some of the characteristics for each model are listed in table 1. The north model incorporates river, general head, no-flow, and areally distributed recharge flux-boundary condition, whereas the south model uses river, no-flow and drain boundary conditions. These combinations of boundary conditions result in flow occurring from recharge sources to areas with extensive ground-water pumping and a consequent widespread lowering of the water table (generally the yellow areas in figures 2A and 2B). Because pumping is substantially less in the south model area than it is in the north model area, flow can continue toward the specified drain along the south model southern border. The south model consists of one layer, whereas the north model was divided into two layers of equal thickness with the lower layer having a larger hydraulic conductivity than the upper layer. This designation is consistent with observations of coarser, more-transmissive sediments in the lower part of the aquifer. Model parameters were estimated in part using MODFLOW 2000 (Hill and others, 2000) to assist model calibration to observed values of hydraulic head in 1972, 1982, 1992, and 1998. Values of the mean, mean absolute, and root-mean-square difference between observed and simulated hydraulic head for all observations for all periods for each model are given in table 1.

OPTIMIZATION MODELING

Optimal sustainable yields from ground water and surface water were simulated at various locations within each model using a modified version of MODMAN (Greenwald, 1998) that permits the optimization of conjunctive use of ground water and surface water (Brian Wagner, U.S. Geological Survey, written commun., 2001). To perform this optimization, each calibrated MODFLOW 2000 ground-water model was converted to MODFLOW 96 to be compatible with MODMAN. Optimization modeling was done to maximize withdrawals at all model cells at which ground-water withdrawals would have occurred in 1997 and at selected river cells, without violating hydraulic head or streamflow constraints. Hydraulic head constraints were based on Arkansas’ Critical Ground-Water Area criterion, which states that if ground-water levels drop below half the original saturated thickness of the formation, then a “critical ground-water area” may be designated.

Optimal surface-water withdrawals were simulated at points along only those streams for which streamflow constraints were specified based on a required minimum flow needed to maintain water quality and fish habitat. Flow into the most upstream point of each river was specified, as were the points at which tributaries connect. Overland flow was distributed equally at river cells within a river reach based on the difference in long-term average streamflow for a specific river reach. Surface-water diversion rates that occurred in 2000 were subtracted from specified overland flow at the appropriate river cells.

Optimized ground-water and surface-water withdrawals simulated for each model are listed in table 1. Simulation of 1997 withdrawal rates to steady-state conditions caused some model cells to go dry or water levels to drop below half the thickness of the aquifer. Because 1997 withdrawal rates could not be sustained everywhere in the models, optimal withdrawals were allowed to vary between zero and the 1997 rates. No additional cells outside those areas that were pumped in 1997 were assumed to be available for pumping. Steady-state conditions were specified for obtaining pumping rates commensurate with sustainable yield (that is, a rate that could be maintained indefinitely without adverse effects). Adverse effects were defined as (1) ground-water levels dropping below half the thickness of the alluvial aquifer or a total aquifer thickness of 30 feet whichever was greater, and (2) streamflow dropping below a specified minimum flow rate. The distribution of sustainable ground-water withdrawals relative to withdrawals in 1997 for each model is shown in figure 2.

Areas at which optimal withdrawal rates are equal to zero are typically distant from the rivers where substantial amounts of induced recharge are not available to wells. Because recharge from rivers is a function of hydraulic head gradient between the specified stage in the river and the head in the adjacent model cells, the gradient and, hence, the recharge rate, is limited by hydraulic head constraints. Wells nearest the rivers are the first to capture induced recharge, depriving wells located farther from the rivers of potential induced recharge.

CONCLUSIONS

The Mississippi River Valley alluvial aquifer supplies large volumes of water for agriculture. Models of ground-water flow showed that pumping at 1997 rates could not be sustained indefinitely without causing water levels to drop substantially below half the thickness of the aquifer. In 1997, total ground water withdrawal was nearly 6 million acre feet per year. In contrast, optimal sustainable yield from the aquifer is about 3.6 million acre feet per year, or about 61 percent of the 1997 rate. Optimal sustainable yield from surface water from rivers for which a minimum flow constraint was specified was about 148 million acre feet per year and could be an alternate supply of water in those areas where ground water cannot meet anticipated demand.

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Table 1. Characteristics of the north and south alluvial aquifer models

Characteristic	**Model Area**	
	North	**South**
Area (square miles)	14,104	3,826
Cells with wells corresponding to 1997 withdrawals	9,979	1,841
Total pumpage in 1997 (acre feet per year)	5,330,000	617,000
Average hydraulic conductivity (feet per day)	230 – 480	250 – 450
Specific yield	0.30	0.27 – 0.30
Specific storage (feet $^{-1}$)	$1x10^{-6}$	$3x10^{-5}$ – $9x10^{-4}$
River cells	1,165	470
Hydraulic head observations	1,698	521
Range in observed hydraulic head values in 1998 (feet above sea level[1])	78 – 298.45	61.85 – 186.01
Mean difference between observed and simulated hydraulic head, all periods (feet)	-0.46	-0.33
Mean absolute difference between observed and simulated hydraulic head, all periods (feet)	4.9	5.1
Root mean square difference between observed and simulated hydraulic head (feet)	6.4	6.5
Optimized sustainable yield from ground water (acre feet per year)	3,019,000	589,000
Optimized sustainable yield from surface water (acre feet per year)	107,307,860	40,886,000

[1] Sea level refers to National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

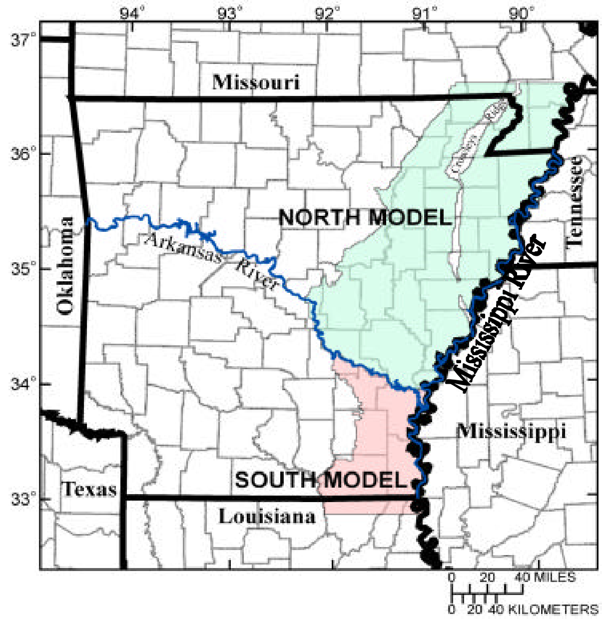

Figure 1. Location of model areas.

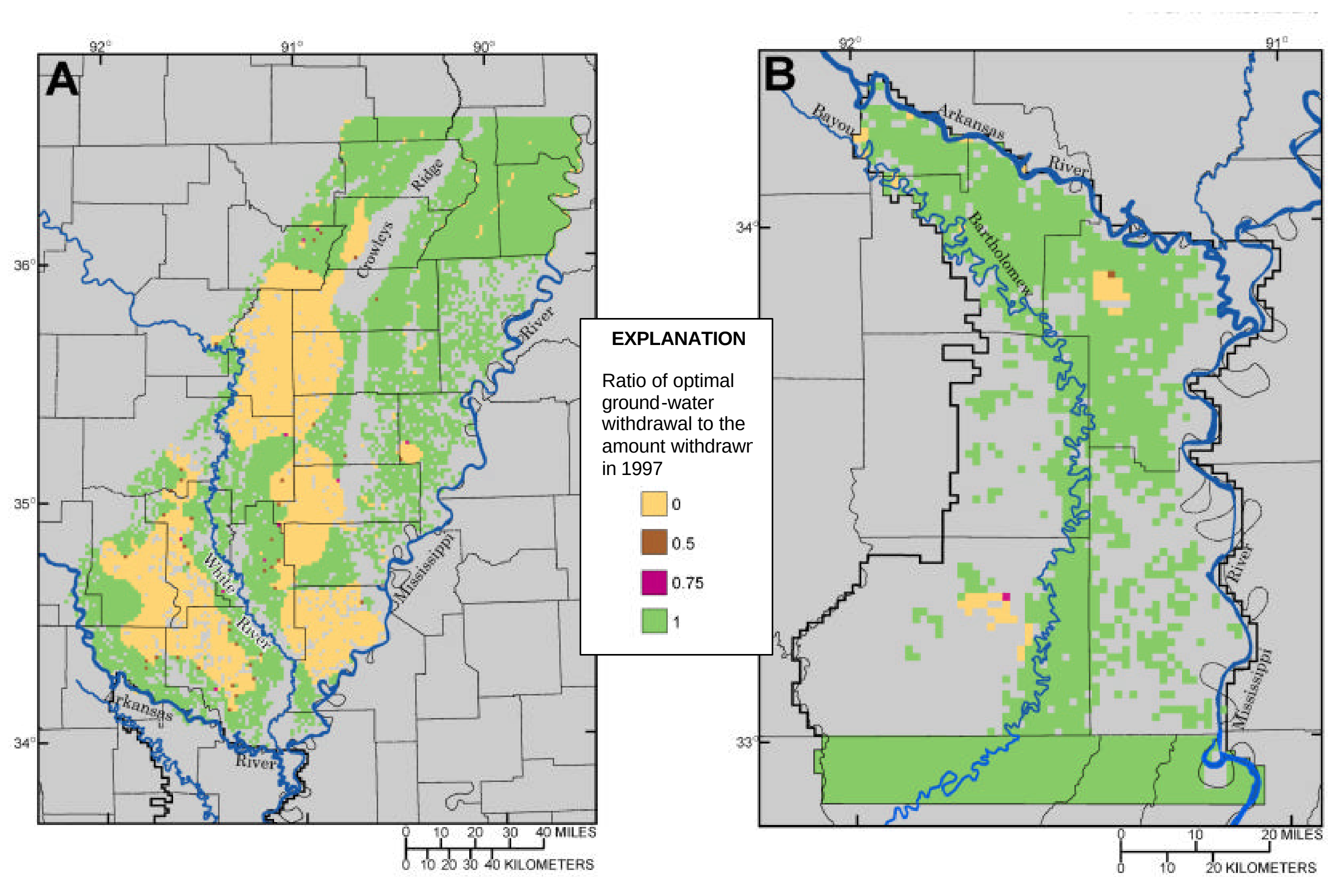

Figure 2. Ratio of optimal ground-water withdrawal to the amount withdrawn in 1997 for (A) the north model, and (B) the south model. Grey areas are either outside the active model domain or areas where no wells were specified in the model.